

SOLAR NEUTRINOS: PROBING THE QUASI-ISOTHERMAL SOLAR CORE PRODUCED BY SUSY DARK MATTER PARTICLES

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ABSTRACT

SNO measurements strongly constrain the central temperature of the Sun, to within a precision of much less than 1%. This result can be used to constrain the parameter space of SUSY dark matter particle candidates. In this first analysis we find a lower limit for the WIMP mass of 60 GeV, well above the WIMP evaporation limit of 10 GeV. Furthermore, in the event that WIMPs create a quasi-isothermal core within the Sun, they will produce a peculiar distribution of the solar neutrino fluxes measured on Earth. Typically, a WIMP with a mass of 100 GeV and annihilation cross-section of $10^{-34} \text{ cm}^3/\text{sec}$, will decrease the standard solar model neutrino predictions, by up to 4% for the Cl, by 3% for the heavy water, and by 1% for the Ga detectors.

Subject headings: Key words: stars: oscillations - stars: interiors - Sun: oscillations - Sun: interior: cosmology - dark matter

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In the last three decades, solar neutrino experiments have measured fewer neutrinos than were predicted by the solar models. One explanation for the deficit is the transformation of the Sun's electron-type neutrinos into other active flavors (Bahcall 1989). Recently, the Sudbury Neutrino Observatory (SNO) has measured the 8B solar neutrinos. The results obtained establish direct evidence for the non-electron flavor component in the solar neutrino flux and yield the first unequivocal determination of the total flux of 8B neutrinos produced by the Sun (Ahmad *et al.* 2001; Bahcall 2001). The total flux of active 8B neutrinos is determined to be $5.44 \pm 0.99 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$, only 10% above the theoretical prediction (Turck-Chièze *et al.* 2001) and consequently in excellent agreement with the predictions of the different solar standard models (Bahcall, Pinsonneault and Basu 2001; Turck-Chièze, Nghiem, Couvidat & Turcotte 2001). Furthermore, this result is also consistent with the measurements in the Super-Kamiokande detector (Fukuda *et al.* 2001).

This work discusses the possibility of using the present 8B neutrinos produced in the Sun to determine a lower limit for the mass of WIMPs, under the standard hypothesis that the Sun's evolution takes place within a halo of non-baryonic dark matter in the form of weakly interacting particles massive (WIMPs). Furthermore, we predict the corresponding neutrino fluxes that should be measured on Earth if the presence of dark matter inside the Sun modifies its evolution.

The dynamic behavior of various astronomical objects, from galaxies to galaxy clusters and to large-scale structures in the observed universe, can only be understood if the dominant component of the mean matter density is dark. The bulk of the dark matter is believed to be non-baryonic, and the existence of particles that interact with ordinary matter on the scale of the weak force, WIMPs, arising from the lightest stable particle predicted by SUSY, provides one of the best candidates to solve this problem (Jungman, Kamionkowski & Griest 1996). In the current cosmological scenario, we are interested in understanding the evolution of the Sun within a halo of non-baryonic dark matter. We assume that the star is in hydrostatic equilibrium, is spherically symmetric and that the effects of rotation and of magnetic fields can be neglected. The present structure of the Sun is obtained by evolving an initial star within a halo of WIMPs, from the pre-main sequence, 0.05 Gyr be-

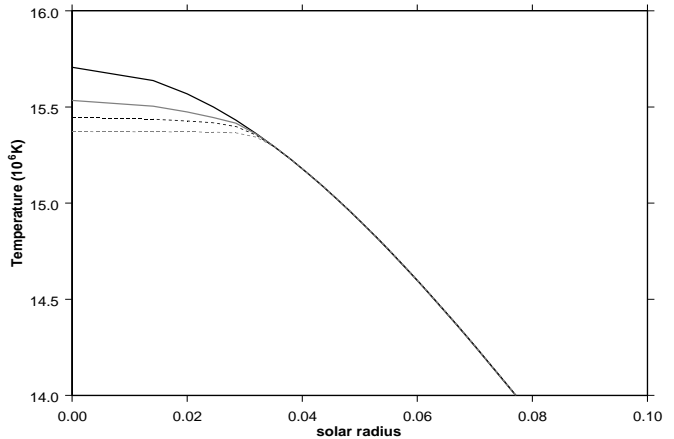


Fig. 1.— This figure presents the variation of the radial distribution of the temperature on the Sun's nuclear region, for the solar standard model and solar models with different concentration of WIMPs in the solar core. The standard evolution of the Sun is represented by the black continuous curve. In the WIMP-accreting models, the evolution of the Sun occurs within an halo of WIMPs with a mass of 100 GeV and annihilation cross-section of $10^{-34} \text{ cm}^3/\text{sec}$. The different curves correspond to the following scalar scattering cross-sections: 10^{-38} cm^2 (grey continuous curve), 10^{-36} cm^2 (black dashed curve) and 10^{-40} cm^2 (grey dashed curve).

fore the ZAMS, until its present age, 4.6 Gyr (Lopes, Silk & Hansen 2001). In such conditions, the WIMPs with masses above 10 GeV accumulate in the center of the star due to their capture by the Sun's gravitational field. Consequently, the present abundance of WIMPs inside the star depends on the number of WIMPs accumulated in the Sun by capture from the Galactic halo and depleted by annihilation. The WIMPs captured during the Sun's evolution are confined in the central part of the nuclear-reacting core of the Sun. The WIMP core radius is inversely proportional to the square root of the mass of the WIMPs (Press and Spergel 1985). WIMP accumulation in the stellar center provides an additional mechanism for transferring radiative energy from the solar core, changing its structure locally. In the particular case of WIMPs with very small scattering cross-sections, or very large mean free paths, the evacuation of the energy of the Sun's core becomes extremely efficient, and the core becomes almost isothermal (cf. Fig.1).

Fig.2a presents the variation of the central temperature of the present Sun in the case of solar models, including WIMPs, relative to the solar standard model. As expected, the maximum effect occurs for stellar models with a scattering cross-section of the order of the critical cross-section, $m_p R_\star^2/M_\star$, where m_p is the proton mass, R_\star is the total stellar radius and M_\star is the total stellar mass. In the case of the Sun, the critical cross-section is of the order of 10^{-36} cm^2 , corresponding to a mean free path of the order of the solar radius. Furthermore, we notice that for very large annihilation cross-sections, the concentration of WIMPs in the core of the star is very small, the structure of the Sun is similar to the solar standard model and, consequently, the central temperature does not change.

The neutrino and energy production in the Sun takes place within 30% of the solar radius. The strong dependence of the nuclear reaction rates on the temperature allows us to use neutrino nuclear reactions such as pp , ${}^7\text{Be}$ and ${}^8\text{B}$ that occur at various locations in the nuclear region to infer the radial distribution of the temperature in the core.

The production of ${}^8\text{B}$ takes place in the inner 2% of the mass of the solar core. ${}^8\text{B}$ decay reactions present the strongest dependence on the temperature: ${}^8\text{B}$ neutrino production is maximum at quite small radii, 5% of the solar radius, and its generation is confined to the region between 2% and 7% of the solar radius. Consequently, this flux of neutrinos becomes the best probe of the temperature at the center of the Sun. Since the temperature dependence of the ${}^8\text{B}$ neutrino flux is strong, the total flux of ${}^8\text{B}$ neutrino production can be expressed as a function of the central temperature of the Sun. Bahcall and Ulrich (1988) computed the central temperature dependence of the ${}^8\text{B}$ neutrinos for 10^3 solar models, and found $\phi({}^8\text{B}) \propto T_c^{18}$. If the SNO measurement of ${}^8\text{B}$ neutrino fluxes is correct, the central temperature of the standard solar model is within less than 0.5% of the temperature deduced from the measured ${}^8\text{B}$ neutrino flux. The central temperature of the Sun is therefore estimated to be approximately $15.78 \cdot 10^6 \text{ K}$. This result is confirmed by the computation of Fiorentini, Villante and Ricci (2001), using the combined results of SNO and Super-Kamiokande.

For comparison, we also estimated the temperature at 10% of the solar radius, which defines the region within which the inversion of the radial distribution of the sound speed is not reliable. Indeed, the nuclear-

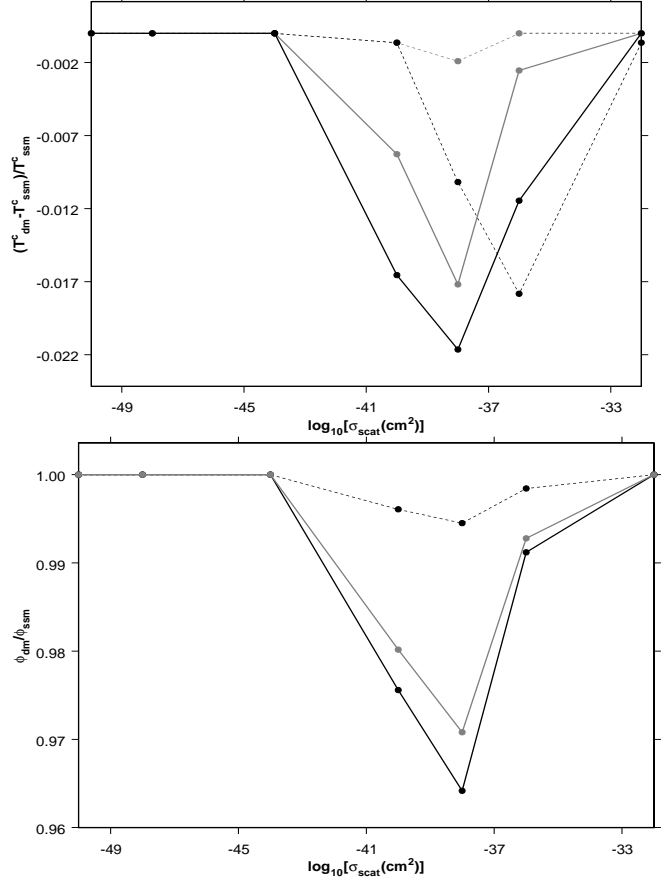


Fig. 2.— **a)** The relative differences of the central temperature between the solar models evolving within a halo of WIMPs, and the central temperature of the standard solar model. The different curves correspond to solar models with the following annihilation cross-sections: $10^{-28} \text{ cm}^3/\text{s}$ (grey dashed curve), $10^{-32} \text{ cm}^3/\text{s}$ (grey continuous curve), $10^{-34} \text{ cm}^3/\text{s}$ (black continuous curve) and $10^{-36} \text{ cm}^3/\text{s}$ (black dashed curve). **b)** The relative variation on the neutrino flux predictions to be measured on Earth by the different solar experiments. The neutrino fluxes prediction of WIMP-accreting models are normalized to the neutrino fluxes predicted by the standard solar model. The different curves correspond to the variation of the solar neutrino flux predictions for the different types of neutrino experiments: ${}^8\text{B}$ (black continuous curve), Cl (grey continuous curve) and Ga (grey dashed curve). The WIMP-accreting solar models have been produced by evolving the star in the presence of an halo of WIMPs of mass of 100 GeV, annihilation cross-section of $10^{-34} \text{ cm}^3/\text{s}$, and scalar scattering cross-section between 10^{-32} cm^2 and 10^{-50} cm^2 .

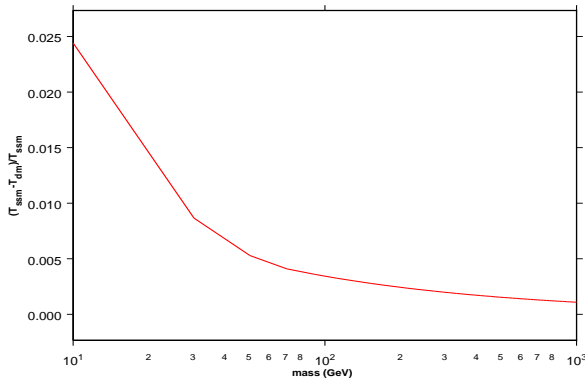


Fig. 3.— The relative differences between the central temperature of the standard solar model and the solar models within a halo of WIMPs.

reacting core is the region of the Sun which is the most difficult to probe with acoustic modes, because it has the least influence on the oscillation frequencies (Lopes 2001, Dziembowski 1996, Gough et al. 1996). It is here that the sound speed has the highest values and the acoustic wavelengths are the longest. Although we have access to about 120 modes to explore the nuclear region, this is quite insufficient to obtain the spatial resolution needed to successfully invert the sound speed in the deep solar core. Furthermore, these modes are strongly influenced by the turbulent motions in the convection upper layers, as well as by the surface perturbations of the magnetic field (Lopes & Gough 2001). The square of the sound speed is proportional to the ratio of the temperature to the mean molecular weight, and it follows that $c_s^2 \propto T/\mu$. The recent sound speed results lead to a small difference between the inverted square of the sound speed and the one obtained from the solar standard model, which is always inferior to 0.6% from the surface towards the center of the star. In particular, at the location of 10% of the solar radius, we have $\Delta c_s^2/c_s^2 \approx -0.002$ (Turck-Chièze *et al.* 2001). If we neglect the variation of molecular weight at this location, the temperature can be estimated to be of the order of $13.041 \cdot 10^6$ K, or nearly 20% of the central temperature of the star. This last point illustrates how the new results of SNO significantly constrain the structure in the region within 10% of the solar radius, comparable to the seismic results. Nevertheless, we notice that the predictions of the standard

solar model are limited by small uncertainties, due to the uncertainties of some physical inputs and to the different treatments of some physical processes occurring inside the star, leading to marginal differences in the central values of the temperature.

It follows from the SNO measurements that any evolutionary model of the Sun that presents a difference from the central temperature larger than $5 \cdot 10^{-3}$, very likely is not a realistic representation of the observed Sun. In Fig. 3, we present the temperature of an isothermal core of WIMPs inside the Sun as a function of the WIMP mass, for the case where the WIMP annihilation rate is relatively small and the annihilation cross-section is smaller than $10^{-38} \text{ cm}^3/\text{sec}$. It follows that models with WIMP masses smaller than 60 GeV produce a variation of the central temperature relative to the solar standard model that is larger than the difference presently estimated between the ^8B neutrino flux and the standard solar model. This type of scenario will be difficult to accommodate in the present context of solar physics. Nevertheless, the WIMP annihilations will modify their total number, leading to an increase of the central temperature and making it closer to the temperature predicted by the standard solar model. This remains true even if the radius of the WIMP core is nearly independent of the annihilation cross-section.

The other neutrino experiments based on chlorine and gallium, present alternative methods for inferring the central solar temperature. In the solar core, the production of pp neutrinos extends from 1% to 30% of the solar radius, closely following the production of energy. The ^7Be neutrinos are produced in the region between 3% and 10% of the solar radius, the maximum production being at around 5% of the solar radius. To a first approximation, the production of neutrinos is almost independent of the solar standard models, and only reflects the nuclear behaviour of the different nuclear reactions where the neutrinos are produced. However, some feedback always occurs due to the adjustment of the luminosity of the solar models to the observed luminosity of the present Sun. Following Bahcall and Ulrich (1988), we obtain that $\phi(pp) \propto T_c^{-1.2}$ and $\phi(^7\text{Be}) \propto T_c^8$. The neutrino flux measured by the different neutrino detectors probes in different ways the neutrinos produced in the nuclear reactions of the pp chain (and CNO cycle). Indeed, the gallium experiment measured 53% of pp neutrinos, 26% of ^7Be neutrinos, 11% of ^8B neutrinos and the rest from CNO reactions and the *hep*

reactions. The chlorine experiment measured 78% of 8B neutrinos and 15% of 7B neutrinos. The different sensitivities of neutrino flux predictions to the solar model with WIMPs is presented in Fig. 2b. As an illustrative example for WIMPs with a mass of 100 GeV, annihilation cross-section of $10^{-34} \text{ cm}^3/\text{sec}$ and scattering cross-section of 10^{-36} cm^2 , the variations in the neutrino fluxes predicted for the different neutrino experiments present a specific signature of the isothermal structure of the core. Even if some physical processes are not correctly implemented or not considered in the treatment of the solar core, such as the abundance of chemical elements, the treatment of the screening of electrons in the nuclear reactions, the treatment of opacity, as well as some dynamical processes related with the magnetic field and the transport of energy by gravity waves, in case an isothermal core is detected by measuring the correct number of neutrinos in the three types of neutrino experiments, this detection will still constitute a very strong indication of the existence of WIMPs in the center of the Sun.

In summary, the results presented here are a first attempt to search for an indirect indication of the existence of dark matter in the solar core, and yields the first predictions of solar neutrino fluxes in such scenarios. The SNO measurements define a lower limit for the WIMP mass to be of the order of 60 GeV, in the case that the annihilating cross section is as small as $10^{-38} \text{ cm}^3/\text{sec}$. This limit is well above the critical mass of 10 GeV, below which the isothermal core cannot form due to the fact that WIMPs can escape the Sun's gravitational field. Furthermore, the quasi-isothermal core of the Sun will create a peculiar distribution in the solar flux of neutrinos. These neutrino fluxes from the core can be measured on Earth by the different solar neutrino experiments. In the case of generic WIMP masses of order 100 GeV and annihilation cross-sections of order $10^{-34} \text{ cm}^3/\text{sec}$, we expect a decrease in the neutrino fluxes, as predicted by the standard solar model, by up to 4% for the chlorine experiments, by 3% for the heavy water experiments and by 1% for the gallium experiments.

The evolutionary models presented in this Letter exploit the possibility of the neutrino fluxes being used to scan the space of parameters of SUSY dark matter particles. Moreover, improved measurements with current and forthcoming neutrino experiments could give us important and unique insights into the existence of a possible isothermal core in the center of

the Sun, that if detected would very likely be created by non-baryonic dark matter particles.

The results obtained here highlight the contribution that solar neutrino measurements on Earth can give us for the understanding of the evolution of the Sun within the dark matter halo of the Milky Way. We have discussed the possible existence of some processes occurring in the solar core that are missing from the standard solar model, which in the near future will be within the reach of solar neutrino experiments. This is particularly true for processes that originate via the presence of WIMPs in the core. In addition, the possible detection of gravity modes by SOHO seismic experiments, such as GOLF (Turk-Chi  ze *et al.* 2001), could ultimately provide a strong constraint on the physics of the solar core, and constitute an alternative probe of the solar center that would complement the neutrino fluxes.

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